

METEOROLOGICAL ASPECTS OF ATMOSPHERIC  
POLLUTION AND POSSIBILITIES OF OBSERVATION FROM SPACE

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METEOROLOGICAL ASPECTS OF ATMOSPHERIC POLLUTION  
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## METEOROLOGICAL ASPECTS OF ATMOSPHERIC AND POSSIBILITIES OF OBSERVATIONS

### I. Introduction

It is known that the main factors determining the earth's climate are the solar radiation flux incoming to the outer atmospheric boundary (the solar constant), atmospheric transparency both for short- and long-wave radiation, the structure of the relief of the underlying surface, etc.<sup>1</sup> Atmospheric transparency is the most variable of the above mentioned factors. It can be supposed that the instability of atmospheric transparency causing fluctuations in the solar energy income to the earth's surface and resulting in variations of the greenhouse effect of the atmosphere is the main reason for the present-day climatic changes.

To predict the climate of the future, an attempt should be made to evaluate the prospects of natural climatic changes and to determine the degree of influence of man's industrial activity. According to Budyko's estimates<sup>1</sup>, for the time period of up to several centuries, the natural factors cannot change the meteorological regime of our planet to a considerable extent. Unfortunately, this cannot be applied to man's industrial activity whose results have long been felt in the earth's climate. Here, it is important that, on the one hand, thanks to the rapid development of industry and the availability of powerful energy, there appeared real prospects for purposeful transformation of climate. At the same time, industrial activity has undesirable (and, for the present, practically uncontrollable) consequences from which the pollution of the earth's atmosphere should be indicated first. It should be emphasized that it is necessary to have an idea of not only direct effects connected with the pollution of the atmosphere and water basins but also the consequences of the pollution, which are secondary phenomena and are much more difficult to foresee and overcome due to the complex mechanism of subsequent dependences.

According to the data<sup>2,8</sup> for the Federal Republic of Germany, the linear growth of population is followed at present by the exponential increase of the factors determining

atmospheric pollution. The rapid development of all kinds of transport (first of all, road and air transport), as well as the intensive growth of industry, lead to increased atmospheric pollution not only in the vicinity of big industrial centers but also over extended territories. Millions of tons of pollution products thrown out annually into the atmosphere by industry spread far beyond the limits of direct sources of pollution. Thus, industrial air pollution should now be considered not as a local or regional, but as a global phenomenon. In this respect, quite illustrative is the permanent increase of the content of carbon dioxide and aerosols in the atmosphere.

In spite of all the serious measures taken to diminish industrial atmospheric pollution, the pollution problem becomes ever more urgent. It has been discovered, for instance, that the meteorological regime of many cities is already substantially dependent upon air pollution<sup>2,68</sup>. A number of investigations (see, for instance, references 2-5) mark the decrease of atmospheric transparency during the recent decades. According to reference 5, from the beginning of the present century, the air turbidity increased by 50 to 80 percent. Papers 6 and 7 give consideration to the possibility of the change of the earth's heat budget and the distribution of precipitation under the influence of global atmospheric pollution. The authors of reference 6 stress that the erosion of soil and the pollution of water and the atmosphere cause an enormous economical damage and threaten man's health.

Special attention is attracted by the appearance during recent decades of sources of pollution to the upper atmospheric layers: high-altitude jet aircraft and satellites. In a number of papers (see, for instance, references 2, 5, 9, 10, 60, and 67), this kind of pollution is considered as one of the probable reasons for the expected change of the climate. From the data in references 9, 10, and 52, as a result of stratospheric pollution caused by the exhaust gases of jet aircraft, the stratospheric water vapour concentration increases, which may lead to changes in the thermal regime and the ozone content in the atmosphere. References 5 and 53 invite the reader's attention to the fact that, beginning with the 50's, a notable increase of cirrus cloud amount has been observed, which is apparently one of the consequences of the increased

number of flights of high-altitude aircraft. Similar conclusions are made in paper 9, according to which the possible effect of 500 supersonic aircraft is an increase of the temperature of the equatorial stratosphere by several degrees.

Among the natural sources of atmospheric pollution, the most important is volcanic activity<sup>1,6,9,52,67,68</sup>. Volcanic dust spreading in the atmosphere after an eruption decreases atmospheric transparency for solar radiation and, thus, affects the climate. It is interesting to note that the degree of this influence depends on the latitude and season<sup>1</sup>, this effect revealing itself most distinctly in the case of global radiation. In the high latitudes, solar radiation decreases more rapidly than in the low latitudes and in winter more intensively than in summer. This regularity is one of the factors causing the growth of temperature variations after volcanic eruptions with increasing latitude<sup>1</sup>.

The influence of the remaining natural sources of pollution (dust, bacteria, spores, pollen, marsh-gases, decomposition products, photosynthesis products, water vapor, fog, etc.) is apparently small and not sufficiently studied.

The climatic effects connected with atmospheric pollution caused by man's industrial activity were investigated in a number of papers. (See references 1, 2, 5, 9, 10, 52, 60, 67, and 68.) In paper 10, the following classification of "industrial" pollutants is suggested: (1) the gaseous components of atmospheric pollution ( $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{SO}_2$ ,  $\text{CH}_4$ ,  $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{NH}_3$ , etc.); (2) the aerosol components of tropospheric pollution; (3) the aerosol components of stratospheric pollution; (4) pollution products in seas, oceans, and rivers (oil, mercury, petroleum, etc.); (5) the so-called "thermal pollution," whose sources are big cities and industrial regions.

The urgent necessity to study the interrelations between the pollution components and the climate impelled many investigators to take up these problems. For instance, a whole series of papers (see references 11-24) is devoted to the subject of the influence of the increasing concentration of atmospheric carbon dioxide upon the climate of the globe. Recently, general attention is becoming ever more attracted by the problem of the global distribution of

pollution. Comprehensive programs of experimental investigations of the spread of pollution over the globe and the elaboration of methods for preventing dangerous industrial pollution (see, for instance, papers 2, 6, 7, 9, 10, 26, 66, and 67) testify to the fact.

The aim of the present review consists in the discussion of the results of studies of the picture of pollution on the planetary scale in its connection with meteorological aspects (the possible influence on the climate), as well as in the consideration of the prospects of remote detection of atmospheric and oceanic pollution from space.

## II. Gaseous Components of Atmospheric Pollution

Atmospheric pollution is connected with the presence in the atmosphere of both the primary pollution components and the secondary products forming as a result of various chemical and photochemical reactions. Among the main gaseous components of pollution are sulphur compounds (chiefly  $\text{SO}_2$ ), nitrogen compounds ( $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{NH}_3$ ), carbon compounds ( $\text{CO}$ ,  $\text{CO}_2$ ), halogens, hydrocarbon compounds, aldehydes, etc. The most characteristic components of industrial pollution are  $\text{CO}$ ,  $\text{SO}_2$ ,  $\text{NO}_2$ ,  $\text{O}_3$ . Table 1 gives (see references 2 and 8) the comparison data characterizing the approximate concentrations of pollution components in the conditions of a pure and polluted atmosphere.

Table 1  
Concentration of Gaseous Atmospheric Pollution Components

Pollution Component	Concentration (ppm)	
	Pure Atmosphere	Polluted Atmosphere
$\text{SO}_2$	$10^{-3} - 10^{-2}$	0.02 - 2
CO	<1	5 - 200
$\text{CO}_2$	310 - 330	350 - 700
Nitrogen oxides	$10^{-3} - 10^{-2}$	$10^{-2} - 10^{-1}$
Hydrocarbon Compounds	<1	1 - 20

According to the data of paper 7, of importance are the following gas and pollution components which are characteristic of the global scale of spreading: (1) CO (the annual output  $220 \times 10^6$  tons, large life duration, very toxic); (2) CO<sub>2</sub> (of special significance because the variations of its concentration obviously influence the globe's climate); (3) SO<sub>2</sub> (the annual production  $146 \times 10^6$  tons, the life duration of which is about 4 days, the increase of its concentration being distinctly noticeable during the recent years); (4) NO<sub>2</sub> (the total amount is approximately four times greater than that of SO<sub>2</sub>, the life duration being about 4-5 days); (5) NH<sub>3</sub> (chiefly of natural origin); (6) N<sub>2</sub>O (chiefly of natural origin); (7) CH<sub>4</sub> (produced by both natural and industrial sources).

It should be stressed that the polluting gases are of importance not only because they are the gaseous components of pollution but quite frequently they stimulate the formation of aerosol. For instance, it is shown in paper 27 that the traces of SO<sub>2</sub> and H<sub>2</sub>S reaching the stratosphere are oxidized and form nuclei under the influence of O<sub>3</sub> and shortwave radiation. Thus, the new formation of large nuclei in the stratosphere takes place. The mean life duration of such aerosols in the stratosphere reaches 10 to 100 weeks. The preservation of the nuclei in the stratosphere can be accounted for by the presence of a constant flux of gases from the troposphere to the stratosphere.

As has been noted above, among the gaseous components of atmospheric pollution a special place is occupied by carbon dioxide. The reason for this is not only the relatively large values of the CO<sub>2</sub> content in the atmosphere but also the peculiar influence of carbon dioxide on the radiation transfer in the atmosphere. Carbon dioxide is characteristic of intensive absorption bands in the infrared spectral region, owing to which it contributes substantially to the so-called "greenhouse" effect.\* The latter effect consists in the fact that the atmospheric thermal radiation caused by carbon

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\*Landsberg (reference 68) was right to note the inadequacy of the term since the usual greenhouse effect is caused not by radiative factors but by a change in the sensible heat transfer between the surface and the atmosphere.

dioxide brings a large amount of radiant energy back to the earth's surface. The change in the carbon dioxide concentration is followed by a change in the atmospheric thermal radiation, which, in turn, leads to changes in the radiation budget of the underlying surface and the corresponding temperature variations.

It should be emphasized that the evaluation of the quantitative effect of the atmospheric temperature change in consequence of the changed concentration of carbon dioxide is still a debatable subject. All the investigators involved in the problem are unanimous in their conclusion about the permanent increase of the CO<sub>2</sub> concentration in the atmosphere in consequence of the rapid growth of industry. The annual increase of the carbon dioxide concentration in the atmosphere is at present estimated as 0.7-1.5 ppm, in dependence on geographical conditions (references 9, 27-30, 67, 68). On the average, beginning with 1958, the CO<sub>2</sub> content increases annually by 0.2 percent. By the year 2000, it may increase by 10-50 percent, reaching 340-400 ppm instead of the present 320 ppm<sup>68</sup>.

Quantitative evaluations of atmospheric temperature changes caused by the change of the CO<sub>2</sub> content in the atmosphere encounter many difficulties. In the first place, for the above purpose, reliable data are required on the transmission functions of not only carbon dioxide but also water vapor, which is an absorbing substance in the same spectral range as CO<sub>2</sub>. Equally necessary is a correct accounting for the overlap of the H<sub>2</sub>O and CO<sub>2</sub> absorption bands. Besides, it should be kept in mind that inconsiderable errors in the values of radiation fluxes may lead to substantial errors in the values of radiative temperature changes.

Secondly, the atmosphere cannot be considered "frozen," i.e., stable from the point of view of the variations of other components of its thermal regime. In the real atmosphere, the thermal regime variations affect, for instance, the sensible heat transfer and the water content of the atmosphere. The latter may in its turn influence the processes of cloud formation. The sensitivity of a cloudy atmosphere to the variations in the carbon dioxide



concentration is, however, somewhat smaller than in the case of a cloudless atmosphere (see references 16, 20 and 23) and this circumstance causes a peculiar feedback connection in the process considered. Finally, the fact cannot be ignored that in consequence of the change in the carbon dioxide concentration the value of the solar radiation absorption in the  $\text{CO}_2$  bands (1.4, 1.6, 2.0, 2.7, 4.3, 4.8, 5.2  $\mu$ ) also changes, which, in its turn, leads to a change in the temperature of the earth's surface and atmosphere<sup>21</sup>.

Laikhtman<sup>30</sup> has drawn an interesting conclusion. According to his estimates, the values of the temperature change with a given increase in the radiation budget, depending upon the initial value of the budget. According to paper 30, this is associated with the fact that the vertical thickness of the layer, which is subject to temperature variations at the change of the radiation budget, is great with a large radiation budget and small with a small or negative radiation budget. For the same reason, the variations of the temperature lapse rate in the boundary layer are small with a large initial radiation budget and increase monotonously with its decrease. For example, at the radiation budget change of  $0.1 \text{ cal cm}^{-2} \text{ min}^{-1}$ , the earth's surface temperature changes by  $0.7^\circ\text{C}$  with the initial radiation budget value of  $0.5 \text{ cal cm}^{-2} \text{ min}^{-1}$ , whereas with its initial value of  $-0.1 \text{ cal cm}^{-2} \text{ min}^{-1}$  the surface temperature change constitutes  $7.8^\circ\text{C}$ . The above mentioned circumstances are undoubtedly important in the consideration of the  $\text{CO}_2$  influence on the climate.

The above mentioned difficulties render to some extent doubtful the reliability of the results of the investigations devoted to the evaluations of the change of the temperature and climate of the globe in consequence of the variations in the carbon dioxide concentration (see references 11-24 and 69). From the viewpoint of the accounting for the instability of atmospheric stratification and the dependence of its water vapor content on the temperature, the calculational model suggested by Manabe and Wetherald (references 22, 24, and 52) should be considered the best for the moment. According to the data of these authors, a doubling of the  $\text{CO}_2$  content in the atmosphere with a cloudless weather must lead to an increase of the earth's surface temperature by

2.92°C, and with average cloudiness conditions by 2.36°C. Thus, by the year 2000 an increase in the earth's temperature on the order of 0.5-0.8°C can be expected, provided the rate of the growth of the CO<sub>2</sub> concentration remains close to that supposed at present (references 9, 23, 24, and 87). An interesting result of paper 22 should be considered the revelation of the peculiarities of the variation in the atmospheric temperature vertical distribution as a result of the change in the CO<sub>2</sub> concentration: With the increase of the carbon dioxide content in the atmosphere, the temperature in the troposphere rises, and in the stratosphere it falls. This is apparently associated with the peculiarities of the variability of the radiative flux divergence values with the CO<sub>2</sub> concentration change: In the troposphere an increase of the carbon dioxide content is followed by an increase of the radiative flux divergences, whereas in the stratosphere, on the contrary, smaller values of the flux divergences correspond to larger values of the CO<sub>2</sub> concentration<sup>31</sup>.

Close attention should be paid to the suggestion in paper 23 of an advanced model of the "atmosphere-ocean" system which takes into consideration both the thermal and dynamic interrelation of the atmosphere and ocean. The evaluations of possible climatic changes with the help of this model show that the thermal relaxation time for the "model" ocean exceeds 100 years. An analysis is also given of the quantitative effect of the influence of ocean currents upon the temperature distribution, relative humidity and precipitation. Further studies using this model can apparently give interesting results relating to many aspects of the investigation and forecast of the globe's climate, including the problem of the influence of the increase in the carbon dioxide content on the climate.

Thus, in spite of numerous efforts and the notable success achieved in the field of studying the influence of the variability of the carbon dioxide concentration in the earth's atmosphere on the climate, the problem under consideration cannot be considered solved, particularly from the viewpoint of the evaluations of the quantitative characteristics of the process. In order to obtain sufficiently reliable results, a correct accounting

for the dynamics and feedback mechanisms of the processes, as well as the estimates of the interrelations between the various factors of the change of the earth's climate are required. In this connection, of great interest are studies of the local influence of pollution upon the radiation regime and climate<sup>59,61,68</sup>.

### III. Aerosol Components of Atmospheric Pollution

The presence in the atmosphere of solid particles of terrestrial and space origin is of great importance for the solution of the problem of atmospheric pollution. Aerosols as condensation nuclei are the main factor of the phase transformations of water in the atmosphere. In certain cases, aerosols exert the dominating influence on the transfer of both solar and thermal radiation in the atmosphere, which is of primary importance in the studies of the factors of weather and climate. It should be stressed that the latter aspect is the central one in the given review.

As has been noted above, aerosols can be of natural and industrial origin. From natural aerosols, only volcanic dust and probably sometimes huge dust storms can notably affect the atmospheric transparency on a global scale. In the recent time, an ever-larger amount of data has been accumulated, testifying to the considerable rate of the increase in the intensity of throwing out into the atmosphere of industrial aerosols. According to the data of papers 2 and 8, the concentration of aerosols in the polluted atmosphere is dozens of times greater than their concentration in the pure atmosphere (0.01-0.02 and 0.07-0.7 mg m<sup>-3</sup>). The climatic effects connected with the solar radiation absorption by aerosols, as well as the harmful effect of some types of aerosols upon the nature make the problem of aerosol pollution quite urgent, especially in the light of the prospects of future rapid development of industry and transport. Numerous investigations are devoted to the study of the chemical composition and optical characteristics of aerosols, the vertical profiles of their concentration, and the size distribution of particles. The works cited in the present review (papers 32-39) are only a small part of these. Along with this, it should be noted at once that the problems

associated with aerosols are so numerous and complex for the most part they are far from being adequately solved.

From the point of view of determining the influence of aerosols upon the radiation regime of the atmosphere, it is extremely important to obtain information on the optical characteristics of aerosols, the vertical profiles of their concentration, and size distribution. Highly significant is the construction of a typical model of atmospheric aerosol describing the characteristic peculiarities of the vertical profile of concentration, the temporal and spatial variations of the aerosol vertical profile. Unfortunately, the available experimental data necessary for this purpose are insufficient, chiefly due to the absence of the network for observations of the aerosol content in a free atmosphere. A comparatively large amount of experimental data on both the vertical distribution of the aerosol particle concentration and the vertical profile of the coefficient of the aerosol attenuation of radiation has been accumulated for the lower troposphere. Nevertheless, it is in the lower atmospheric layers that we come across the greatest difficulties when constructing the aerosol model: the necessity of accounting for the influence of the underlying surface and the surface sources of aerosols, as well as the condensation and coagulation processes<sup>35</sup>. The data of Berliand<sup>38</sup> also reveal how difficult it is to determine the field of aerosol concentration. It can be seen from these data that in some geographical zones characteristic of intensive turbulence large values of the surface concentration of pollution from high sources must be observed, as compared to other regions, the source power being the same and the other conditions being equal.

Thus, the knowledge of optical and microphysical characteristics of atmospheric aerosol, as well as its spatial distribution in the atmosphere, cannot be considered adequate at present<sup>40,41</sup>. For this reason, the information contained in papers 32-39 on individual actual aerosol stratifications or generalized aerosol models should be considered as preliminary steps in the investigations which will finally result in a reliable

determination of the laws governing the aerosol field in the atmosphere. The available experimental data enable us to conclude the following (see reference 34):

1. The vertical distribution of atmospheric aerosol has a stratified character.
2. The most stable aerosol layers are those over the tropopause and at heights 17-23 km.
3. A definite connection exists between the aerosol and temperature profiles in the troposphere and stratosphere.
4. Aerosol layers are characteristic of a large horizontal extension and homogeneity.
5. The optical density of atmospheric aerosol in the upper troposphere and stratosphere may vary within nearly two orders of magnitude.
6. The size distribution of aerosol particles varies substantially with height and can be described only approximately by the Junge formula.
7. Hygroscopic particles constitute the majority of aerosol in the upper troposphere and stratosphere.

Although the influence of aerosol upon the radiative and thermal regime of the atmosphere and, consequently, upon the climate is doubtless practically, there are no reliable quantitative evaluations of this effect. Unfortunately, at the moment, there is no generally used calculational scheme which would permit determination with sufficient accuracy of the contribution of aerosol to the attenuation and especially absorption and emission of radiation by the atmosphere. Paper 55 is the only one that gives the first experimental data on the true absorption of shortwave radiation by aerosol. The main reason for this situation is, as is well known, not only the difficulties associated with accounting for the optical properties of aerosol but also the substantial variability and diversity of initial information: Even using the simplest scheme for the calculations, it is necessary to take into consideration both the absorption

(emission) and the scattering by aerosol particles. In order to obtain initial data, it is necessary to perform in each particular case a rather complex experiment to determine the size distribution and vertical profile of aerosol particles. Complex experimental programs involving simultaneous radiation and aerosol measurements were performed only in the most recent time<sup>54, 56</sup>.

Thus, the conduction of numerical experiments to study the influence of the variation of the aerosol structure of the atmosphere upon the globe's climate, even in the first approximation (as has been done, for instance, for carbon dioxide<sup>11-24</sup>), is at present a matter of considerable difficulty.

The problems associated with the difficulty of accounting for the contribution of aerosol effects to the theory of radiation transfer in the earth's atmosphere appear to be an essential obstacle to a successful development and adjustment of calculational methods for studying the influence of radiative factors upon the thermodynamics of the atmosphere. The results obtained in this direction are only preliminary. Theoretical calculations in agreement with experiment<sup>54</sup> point out the fact that under certain conditions (considerable atmospheric turbidity) the presence of aerosol greatly influences the infrared (thermal) radiation transfer, resulting in an increase of radiative cooling. However, more typical should be considered such a situation when this influence is only slightly notable. In the presence of aerosol, an increase of the planetary albedo obviously occurs, i.e., the value of the absorbed solar radiation decreases and, consequently, the temperature falls. The prevailing point of view at the moment is that, if an increase in the carbon dioxide content leads to a temperature rise, an increase of turbidity is followed by its fall<sup>9, 52</sup>.

The very thorough calculations made by Yamamoto and Tanaka<sup>65</sup> show that, on the average for the globe, an increase in atmospheric turbidity (characterized by the turbidity coefficient  $\beta$ ) is followed by an increase of the albedo (and, consequently, by a decrease of the absorbed solar radiation and a temperature fall). Table 2 presents calculational results illustrating this conclusion.

The calculations considered have been made for two values of the complex index of refraction of aerosol particles with a constant real part ( $n_r = 1.5$ ), and two versions of the imaginary part:  $n_i = 0$  (no absorption) and  $n_i = 0.01$  (absorbing particles). The calculations were made taking account of the relationship between the land (the albedo equals 0.15) and ocean (the albedo equals 0.05).

Table 2  
Variation of the earth's albedo for a cloudless atmosphere ( $A_0$ ) and average cloudiness conditions ( $A$ ) in dependence on the turbidity coefficient

$n_i$	$\beta$	$A_0$	$A$	$\Delta A$	$T_e (^{\circ}\text{K})$	$\Delta T_e (^{\circ}\text{K})$
0.0	-0-	0.1455	0.3228		254.1	
	0.125	0.1904	0.3452	0.0224	252.0	-1.9
	0.25	0.2257	0.3629	0.0177	250.3	-1.7
				0.0218		-2.2
	0.5	0.2694	0.3847		248.1	
0.01	-0-	0.1455	0.3228		254.1	
	0.125	0.1726	0.3363	0.0135	252.8	-1.3
	0.25	0.1947	0.3474	0.0111	251.8	-1.0
				0.0137		-1.4
	0.5	0.2221	0.3611		250.4	

The cloud amount is assumed to equal 0.5, and the albedo of clouds equals 0.5. In the last column of Table 2, the value of the earth's effective temperature is given, which was calculated from the ratio:  $\pi R^2 S_0 (1 - A) = 4 \pi R^2 \epsilon T_e^4$ , where  $R$  is the earth's radius,  $S_0$  is the solar constant,  $\epsilon$  is the Stefan-Boltzman constant.

Although the calculations of Yamamoto and Tanaka<sup>65</sup> are irreproachable from the point of view of the method for calculating the radiation fluxes, it should be noted that

the initial parameters used by the authors may appear to be not quite adequate. Thus, for instance, the value of the ocean surface albedo is definitely lower than in reality. Besides, it would probably be useful to take into account the high albedo of polar regions and deserts. In this connection, it should be noted that the above presented viewpoint, according to which an increase in turbidity is always followed by an increase of albedo and a temperature fall, must be considered somewhat schematic. There is no doubt that in reality the aerosol effects are more diverse and complicated. As to the qualitative evaluation of these effects, it is obvious that with a high albedo of the earth's surface an increase in atmospheric turbidity will lead to a decrease of the albedo of the "earth's surface-atmosphere" system (i.e., to heating). The opposite must take place with a low surface albedo. Of great importance also is the ratio of absorption to backscatter of solar radiation by the atmosphere. Mitchell<sup>63, 64</sup> performed an interesting analysis of the influence of all these factors.

By making use of the approximative parameterization of the shortwave radiation transfer in the atmosphere, Mitchell obtained the following simple formula for the albedo of a turbid (cloudless) atmosphere,  $A_e$ :

$$A_e = A_s - 2A_s a + (1 - A_s)^2 b \quad (1)$$

Where  $A$  is the surface albedo,  $a$  and  $b$  are the portions of solar radiation absorbed and backscattered by atmospheric aerosol, respectively. It can be seen from this formula that with a high albedo,  $A_e < A_s$ , even with a comparatively small absorptivity. Assuming that  $A_e = A_s$ , the critical ratio  $(a/b)_{crit.}$  can be found which determines the conditions for a transition from heating to cooling (or vice versa):

$$(a/b)_{crit.} = \frac{1 - A_s}{2 A_s} \quad (2)$$

Table 3 presents the values of  $(a/b)_{crit.}$  for various conditions.



Table 3

Critical ratio of absorption to backscatter by aerosols, corresponding to zero albedo change, for representative surface types

Surface Type	$(a/b)_2$
Urban areas	1.6
Deserts	0.8
Prairies and farmland (growing season)	1.6
Forests	2.2
Oceans (mid-latitude)	5.2
Snowfields (stable)	<0.1

It can be seen from the above table that only for oceans absorption must be high enough to ensure heating. In all the remaining cases,  $A_e < A_s$  is quite possible, i.e., the effect of heating by aerosol. Having analyzed more complicated models of a cloudy atmosphere, Mitchell<sup>63,64</sup> came to the conclusion that under any conditions aerosols tend to warm the earth if they absorb more than about four times as much solar radiation as they backscatter. Naturally, it should be emphasized that in order to obtain estimates for the conditions of the real atmosphere, it is highly significant to determine the parameters under consideration on the experimental basis.

Speaking of the influence of atmospheric aerosol on the climate, it is necessary to take into consideration the possibility of its indirect effect on the thermal regime of the atmosphere at the formation of cloudiness. Since aerosols are for the most part condensation nuclei, their presence in the atmosphere, other conditions being favorable, is conducive to the formation of haze, fog, and clouds which, as is known, are the main regulators of atmospheric energetics.

It follows from the above said that the investigations of the influence of aerosols on radiation transfer have become most

urgent today because without the solution of the "aerosol problems" it is impossible to answer the numerous questions in the field of studying the interrelations between the radiative characteristics, general atmospheric circulation, and climate.

#### IV. The Experience of Elaborating Remote (Satellite) Methods for Determining Atmospheric Pollution Components

The great achievements of satellite meteorology consisting above all in the creation of meteorological space systems in the U.S.S.R. and U.S.A. to obtain meteorological information on the planetary scale have opened new horizons in the field of studying the earth's atmosphere, weather, and climate<sup>42</sup>. A substantial part of these investigations is the solution of so-called "inverse problems," i.e., problems associated with the elaboration of indirect methods for determining meteorological parameters and characteristics of the underlying surface from the data of measurements of the outgoing radiation from satellites. Marked success has already been achieved in the field of thermal atmospheric sounding<sup>43</sup>. Principal possibilities undoubtedly exist to obtain, by making use of these methods, information on the composition of the atmosphere and the vertical distribution of its different components. The first steps have already been taken in this direction. (See references 2, 6, 7, 9, 10, 43-49, and 66.) Here it should be stressed that the main attention in these investigations is concentrated on the determination of atmospheric pollution components from space. The main aspects of the investigations of atmospheric pollution are (papers 6, 7): (1) the determination of the size and location of main polluted territories (cities, industrial regions); (2) the revelation of the regularities of the spreading of polluted air masses; (3) the determination of the interrelations between large synoptical systems and polluted air masses; (4) the compilation of the picture of the global structure of atmospheric pollution; (5) the determination of the influence of atmospheric pollution on the planetary thermal budget and, consequently, the weather and climate.

Various principal possibilities can be imagined for detection and determination of the concentration of atmospheric pollution components from satellites. For instance, the method of absorption spectroscopy can be used by registering the solar radiation absorption spectrum in the atmosphere at sunrise and sunset relative to a satellite when solar rays penetrate through the atmospheric thickness<sup>48</sup>. It is obvious, however, that this method (which is often called the "occultation technique") is inapplicable to lower atmospheric layers where the attenuation of radiation is too great; and, therefore, the measured signal equals zero, whereas it is the study of lower atmospheric layers that is of the highest interest.

If it were possible to perform the measurements of the reflected and scattered-by-the-earth solar radiation in the ultraviolet or visible spectral region, one might try to make use of the existing spectral peculiarities of the outgoing shortwave radiation caused by the existence of absorption bands with a number of pollutants. (This, above all, applies for  $\text{SO}_2$ ,  $\text{NO}_2$ , and  $\text{O}_3$ ). This method, however, can hardly be used in practice because the above mentioned spectral peculiarities are revealed but slightly, whereas such factors as the reflection from the earth's surface and the scattering (as well as the absorption) by solid particles (aerosols) make it very difficult to interpret the data, since they are both variable and considerable from the point of view of the influence on the outgoing radiation field. This situation is aggravated by the fact that the above mentioned gases have absorption bands, first of all, in the ultraviolet and visible spectral regions (300-655 nm) where the influence of the factors complicating the interpretation of observational data is strongest.

Rather promising seems to be the interpretation of measurement data in the ultraviolet and visible spectral regions performed by means of the correlation spectrometry (references 2, 6, 44, and 47). This method implies the use of a correlation spectrometer in which the measured outgoing radiation spectrum is "modulated" by a given comparison spectrum. The similarity between both spectra is detected from the pulsations of the output signal. The amplitude of this signal serves as the quantitative characteristic of the

content in the atmosphere of the component sought. This method is suggested for determining the content of  $\text{SO}_2$ ,  $\text{CO}_2$ ,  $\text{NO}_2$ , and  $\text{O}_3$  in the atmosphere. It should be noted that aircraft tests performed to determine the sulphur dioxide content (from the data of measurements near the wavelength  $3150 \text{ \AA}$ ) gave promising results. Also promising is derivative spectrometry<sup>62</sup>.

As has been convincingly shown by the development of satellite meteorology, the most promising for the solution of problems connected with the study of the composition and structure of the atmosphere is the use of the data of spectral measurements of the outgoing thermal radiation<sup>43</sup>. According to works 2, 7, 49 and 66, this conclusion holds true also for the solution of the problem of determining the content of atmospheric pollutants.

It should be emphasized that the problem of obtaining information on the content of pollution components in the atmosphere from the outgoing radiation spectra study puts forward quite a number of strict requirements to the corresponding experiment. The first necessary condition for the successful solution of the problem consists in the finding of such a spectral interval where the absorption spectra of the considered component and the others do not overlap. Such a condition can be obviously better satisfied by way of selecting narrow enough spectral intervals. Therefore, radiation detectors used on satellites in such experiments must have a great resolution ( $<0.1 \text{ cm}^{-1}$ ), as well as a high sensitivity and a possibly low time constant<sup>7</sup>.

As has been noted in work 7, the detection of pollution components from the data of spectral measurements of reflected solar radiation or their own thermal emission makes it possible to obtain information also on the vertical profile of the concentration of the studied pollution gases. In this connection, it should be mentioned that in the solution of the problem of determining the vertical profile of the concentration of the pollution component, absolutely necessary are the data on the vertical temperature profile. (As is known, the outgoing radiation is chiefly determined by the vertical

distributions of the temperature and concentration of the polluting component.) Since at present the problem of atmospheric thermal sounding from satellites can be considered as practically solved (see reference 43), this circumstance meets with no difficulties. Moreover, the mathematical methods worked out for the solution of the problem of thermal sounding can also be applied for the interpretation of the outgoing radiation measurement data for the purpose of determining the content of pollution components.

In this connection, of great importance is the discovery during the solution of inverse problems of satellite meteorology that the solution is essentially dependent upon the correctness of the kernel of the integral equation of the problem, i.e., the reliability of determining the transmission function (references 2 and 7). The available data on the transmission functions of the above considered polluting components of the atmosphere can be considered but tentative. There is no doubt, therefore, that the insufficient spectroscopic knowledge of these components is a serious obstacle to the elaboration of satellite methods of the determination of their content in the atmosphere. Although at the moment a complex approach to the solution of inverse problems is being worked out and it assumes the use of the outgoing radiation measurement data for the independent determination of the derived transmission functions, the method cannot be considered practicable so far.

The available results of the investigations conducted in connection with the solution of the problem of determining the vertical profile of humidity show that one of the most serious difficulties is caused in the given case by the "bad" weighing functions determining the vertical distribution of the relative contribution of individual atmospheric layers to the outgoing radiation (reference 43). Apparently, the same difficulty must be characteristic for the solution of the problem of the content of pollution components as well.

It should be mentioned that a good deal of useful information on atmospheric pollutants can be obtained on the basis of the analysis of the earth's photographs taken from

satellites (papers 6, 10, and 46). For instance, it has been noted in paper 6 that the analysis of photographs taken from the Gemini spacecraft showed that it is possible to compile maps of the location and paths of the motion of polluted air masses. Various photographic methods for the investigation of the global distribution of polluted air masses both in the visible and infrared spectral regions are also suggested in works 46 and 57. As has been revealed by the analysis of the spectra of the earth's twilight aureole obtained from the Soyuz-5 manned spacecraft<sup>58</sup>, such measurement data opens broad possibilities for obtaining information on the planetary distribution of aerosol.

Finally, it should be noted that the above considered results of the investigations using the method of emission infrared spectroscopy are relevant to the case of a cloudless sky. This means that the application of the measurement data to the real conditions will give rise to the same problems of accounting for the influence of cloudiness that take place in the well-known case of atmospheric thermal sounding. The situation will be even more complicated because of the importance of determining the concentration of pollutants near the earth's surface. Although, according to Ludwig<sup>7</sup>, the comparison of the measurement results for cloudy and cloudless conditions facilitates the determination of the vertical profile of the pollution components, the accuracy of the experiment in the presence of cloudiness apparently cannot be considered adequate.

As with the problem of thermal sounding, the solution to the problem of the influence of cloudiness can probably be sought through the microwave spectral region. However, the considerable overlap of numerous spectral lines of individual atmospheric components makes it rather difficult to use the microwave region.

The above considerations concerning the principal possibilities and methods of determining the concentration and vertical profiles of atmospheric pollution components represent only one aspect of the problem of the investigation of atmospheric pollution. The global character of this phenomena requires, apart from the elaboration of the measurement methods and the instruments, a well-grounded

and thought-out organization for the collection of such experiments which should be complex and worldwide. Some ideas and suggestions concerning the subject are presented in works 6, 10, 45, and 66. Paper 45, for instance, describes various types of information systems used at present in the U.S.A. in the programs of atmospheric pollution control. The systems include the following components: (1) a network of automatic instruments for permanent determination of the content in the air of the main pollutants ( $\text{CO}$ ,  $\text{SO}_2$ ,  $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{O}_3$ , hydrocarbons) and instruments for meteorological control; (2) means for the transmission of information obtained (telex, etc.); (3) a center for the processing, analysis, and generalization of data received from different control stations, performed with the help of computers.

The authors of paper 6 emphasize the necessity for the organization of the "Air Pollution Service." They also suggest a detailed program for the organization and processing of the observational data. The main items of the program are: (1) comparison of satellite and surface measurement data, taking into account discrepancies caused by the presence of cloudiness; (2) determination of the average quantitative characteristics of air pollution by dividing the observed territories into squares (or sectors) whose boundaries are selected in accordance with the location of pollution sources; (3) obtaining additional information to produce more accurate results and more detailed data through measurements with the help of aircraft, radiosondes, lidars, and radars; (4) determination of the correlations between satellite and surface data; (5) determination of the quantitative characteristics of atmospheric pollution and the directions of the motion of polluted air masses for the considered concrete synoptical situations. (For such kind of calculations, calculational schemes should be worked out beforehand which would provide sufficiently accurate results.)

As a result of regular measurements and analysis of the information obtained, a reliable picture of the present state of atmospheric pollution should be established, the regularities of the geographical and vertical distribution of air pollution must be investigated, and the prospects for further studies, outlined. Realization of the above

mentioned persons would provide the necessary initial material for reliable evaluations of possible climatic changes under the influence of atmospheric pollution, as well as for taking the necessary technical and organizational measures to avert the harmful consequences of air pollution and planning the use of territories for housing and industrial building, agricultural purposes, etc.

#### V. Thermal Anomalies of Industrial Origin

According to Budyko<sup>1</sup>, the annual quantity of energy presently consumed per unit of surface equals  $0.02 \text{ kcal cm}^{-2}$  on an average for the land taken as a whole. In regions with dense population and a high level of industrial development, this value is much greater--up to  $100 \text{ kcal cm}^{-2} \text{ year}^{-1}$ . It is obvious that all the used energy is finally transformed into heat. Since the main part of this energy is a result of the photosynthesis which took place in the previous epochs (the energy of coal, oil, etc.), in our time it is a new source of heat, in addition to the heat of solar radiation. Thus, big cities and industrial regions are, in a way, "heat islands"<sup>68</sup>, causing anomalies of the atmospheric temperature. As a result of the combined influence of geographical and meteorological conditions characteristic for a given region and the artificial "weather warming," a specific micro-climate of the region under consideration is formed. It can be supposed that the existence of such "thermal pollution" affects (or will affect) to some extent the heat regime of the whole globe, the more so that the quantity of consumed energy increases nowadays. According to Budyko's estimates<sup>1</sup>, at present the annual increase of energy used all over the world constitutes 4 percent, which means a doubling of its amount every 17 years. In this case, the total amount of the energy produced will reach the value of the radiation budget of the land in less than 200 years. In the opinion of some other authors, this increase is even more considerable and amounts to 10 percent. Apparently, in the future it will be necessary to work out special methods for transmission of superfluous heat into space, without which a considerable overheat of the globe will be inevitable.



Such calculations are certainly conditional enough, since it is difficult to evaluate at present whether such an enormous increase in the production of energy will be necessary for industrial development in the future. This consideration, however, does not reduce the urgency of studying the natural and geographical distribution of "thermal pollution," as well as the degree of its influence upon the climate. In this regard, ample and useful information can apparently be obtained by way of thermal sounding of the atmosphere from satellites (see papers 2 and 43).

Speaking of large amounts of energy being transformed into heat through burning, it should be kept in mind that, in the process of burning, oxygen is consumed and that one of the products of burning is carbon dioxide. As a result, on one hand, the content of carbon dioxide in the air increases (as has been noted above) and, on the other hand, the amount of vitally necessary oxygen decreases. According to Davitaya<sup>51</sup>, the diminution of oxygen for the whole anthropogenic period and that for the past 50 years, as a percentage ratio, constitute the same value of about 0.02 percent. For the burning of the main kinds of fuel, about 13 million tons of oxygen are consumed. An annual increase of the oxygen consumption equal to 10 percent seems to be quite realistic. This means that during the next 50 years 0.77 percent of the presently available amount of free oxygen of the atmosphere and hydrosphere will be spent. However, by the year 2070 the total amount of consumed oxygen will reach the critical value of 1,005,200 milliard tons, or 66.7 percent of the present reserve. Such a diminution of oxygen will be a serious danger to man. Here it should be noted, though, that the above conclusions are the result of a simple extrapolation of the present-day state of the matter on the future. Partially for this reason, the authors of papers 9, 58, and 67 reject the theory of the dangerous diminution of the oxygen amount and do not see any problem regarding oxygen.

To sum up the above, it can be concluded that the main point in the solution of the problem of planetary atmospheric pollution and its possible influence on the climate consists, above all, in obtaining reliable information about pollution. There is no doubt that observations from space are most

adequate for this purpose. An important role is also played by current experimental programs for the investigation of the pollution picture and optical characteristics of the atmosphere with the help of satellite and conventional (surface, aircraft, balloon) observation means.

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